SPACE TOURISM, SCALING UP

A Thesis

Presented to

the Faculty of the Department of Mechanical Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

in Space Architecture

by

Bradley Richard Gould

December 2018

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Abstract

The space industry, typically known for research and exploration, is transitioning into commercial ascendancy. Tourism could be a strong catalyst for the success of the industry, as more interest means more dollars. The challenge lies in a distant break-even point; all enterprises thus far have tapped out. One strategy to overcome this hurdle is to increase the number of customers. The purpose of this work is to demonstrate a strategy for accommodating the growth of the space population from tens to hundreds to thousands, identifying limitations that must be overcome and opportunities to be found along the way.

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Chapter 1

1.1 Introduction

Space tourism was envisioned centuries ago. It has now been attempted, more than a handful have even succeeded, (Waldek) but it is still in an early stage of its formation. The financial hurdle of space access currently lies in the problem that it costs a good deal of effort to move weight off earth. During this nascent phase, participation is restricted to tax funded employees of governments and the brave affluent. This is the outcome of a natural growth curve and should not be rejected; likewise, the first airplane seats were quite expensive, but in time costs fell and the low fare ticket matured into a significant portion of the pie. Objections abound for the idea, yet "despite long delays... it is a matter of when not if commercial space travel becomes commonplace. "Technology will advance, demand will expand, and the costs of launches and tickets will fall, driving the innovations that should help make this a reality for generations to come" (Heracleous). While it is particularly difficult to imagine how we transition from where we are now to then, the inconceivable today is inevitable tomorrow.

1.2 A Slow Ball Rolling

From a broad perspective, you would be hard pressed to find many in the space industry who would agree if you were to claim that the industry has been thriving. It is of course not easy. Aside from the financial burden of research and technological development, the physical hazard to the human body, the challenges regarding legislation, and the cost of failure can be irretrievable. To date it is an unquestionably poor investment, as it has not been substantiated as a viable economic industry. This is a misleading metric, however, as the industry has historically been focused on research and exploration over profit seeking. Looking forward, companies understand that a solid financial footing is necessary, yet every tourism related attempt thus far has tapped out. The fundamental flaw of any space enterprise is that it is prohibitively expensive, limiting its market and increasing its market risk. Currently, companies are selling tickets at a loss. Just to visit the Karman line, space's technical boundary, for a five-minute freefall, "customers (are) each paying $300,000... with Blue Origin, barely scratching the surface of the tens of millions each launch will cost" (Heracleous). While we are in the demand generating phase of this conquest, behaving counterintuitively can get the ball rolling, engaging in tactics such as "giving new customers a deal, and creating an exclusive club." says Firas in 5 Strategies for Generating Consumer Demand (Kittaneh). Space tourism's initial customers are ultra-rich, but the revenue from this small market is limited. To expand the total addressable market, we can either give more or ask for less. Providers cannot yet afford to make the product interesting enough for the customer to justify the cost, and they continue to fail. Yet if they can't lower prices enough to attract customers, artificially if necessary, history will repeat. It's a chicken and egg scenario, a solution must be found sooner rather than later as our companies are slipping into debt, to join the others.

There are several budding entrepreneurs dreaming to get in on the action, but few will be able to. The cost to build a station is oppressive. There are many complex systems that must be developed, all of them nearly unproven and most of them prohibitively expensive. Investors are taking notice. Those backing the movement may be able to assist by spreading out the upfront costs over time to stabilize the equation. Another tactic used in business when costs are too great is to limit your offering, also known as specialization. Space companies are familiar with this, often splitting up a project based on areas of expertise and teaming up. Some attribute our spirit of cooperation to the necessity of collective survival.

1.3 Reaching into a new market

A promising strategy is to take advantage of economies of scale efficiency, offering lower prices to a greater number of customers. The theory of the diffusion of innovation (Rogers) reveals that to make a profit, companies must break into a market beyond the innovators and early adopters, reaching across the infamous chasm into early market majority. The hallmark of this untapped market is in the name

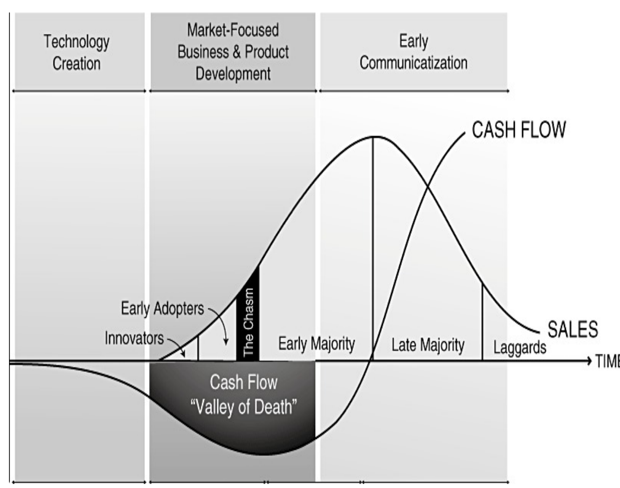


Figure 1.3 1 Diffusion of Innovation

-*majority*, there are many. This is difficult to imagine because it requires unveiling the cognitive dissonance regarding scale. The idea of many astronauts on a spacecraft summons implausible images of a far off sci-fi future, so it is challenging to confront the truth that we must think orders of magnitude greater. To access a market large enough to draw the kind of return on investment that the banks are betting on, it requires the scale to be turned way up, and so far, this is unprecedented. Fundamentally, we cannot lower ticket costs until we have moved beyond the period of drastically increasing the number of sales.

There are businesses that only target wealthy customers, but neither group can be excluded in this case. We must "build a hybrid model catering to both ends of the spectrum... [just as] most airplanes have first-class and coach seating" (Sanders). If we found an opportunity to make space accessible to a greater population, the overview effect alone could transform our world.

1.4 The Rate of Growth

The Cislunar 1000 is ULA's 30-year roadmap of cislunar economic growth. The population, representative not only of tourism but of manufacturing, mining, and other labor trades, grows to twenty in the first five years. Considering that there are over a dozen researchers on the ISS today, this is a conservative estimate. In the following decade, however, the population grows an order of magnitude to 300, and the rate of change flatlines after that to reach only 1000 in another 15 years. Every five years, the estimated capacity of a single commercial space station is expected to double. If in 2020 the first four passengers make their mecca, we might calculate this number to reach 1000 near 2060, as seen in Table 1.4 1. This

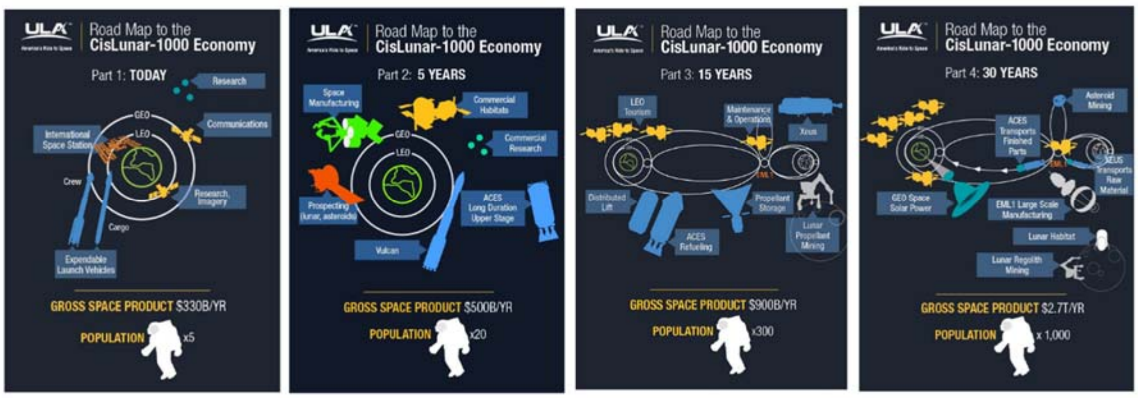
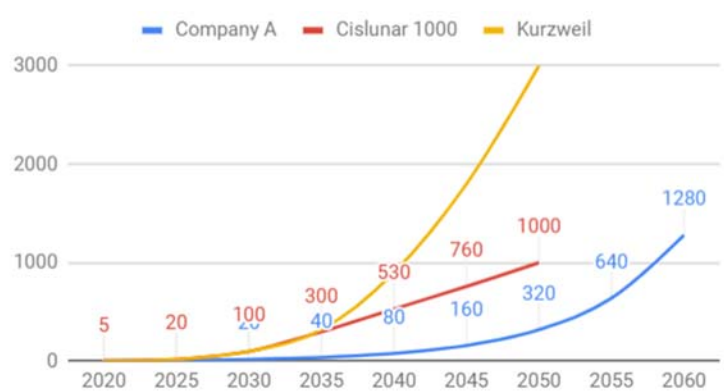


Figure 1.4 1 Cislunar 1000 Economy

seems suspiciously far off; the industry has an unhealthy fear of overcommitting and the result has been underperforming. The baseline this establishes looks like decades of pricey flights for deep-pocketed and able-bodied passengers, no students, no elderly, no kids, no young parents, no teachers, and no artists. This isn't changing the world, yet it could. We need to move as swiftly as possible from an Elysium scenario to widespread acceptance.

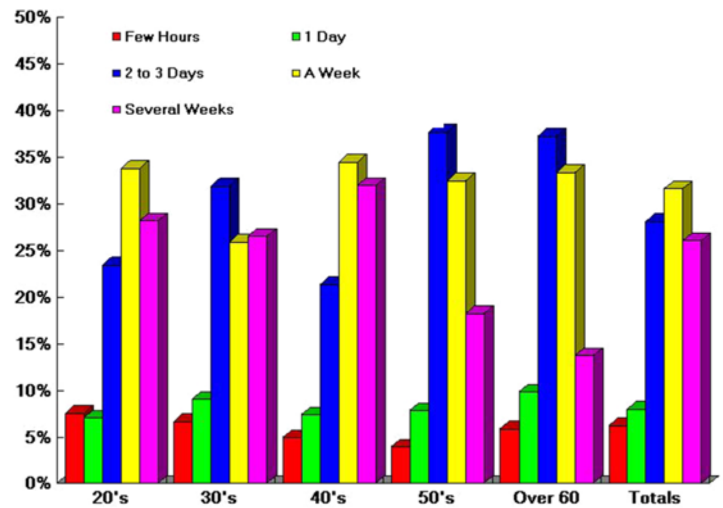
Table 1.4 1 Cislunar Population Growth



The momentum may generate slowly, yet the prediction for the rate of growth of this company is correct. Kurzweil's law of accelerating returns states that change is exponential (Kurzweil). Under this theory, our overall population should multiply not to 1000 but to 3000 by 2050. In the early 1900's the birth of the Model T and the perfection of the assembly line changed the streetscape dramatically and swiftly. In a short few years the cities went from a leisurely pace of horse and carriages, bicycles, and a rare motor, to a nearly total takeover. This sudden paradigm shift for most was unimaginable, yet in the span of one's childhood it became reality. This is the nature of logarithmic growth; it takes energy to set up but less to continue, allowing that energy to be reinvested, resulting in an accelerating growth curve. We aren't suggesting that minimum wage employees will be able to go to space next year; the first passengers must still be wealthy, it will take time for the cost curve to mature, but their chance will come sooner than expected. 1000 is not a magic number, but it is big enough to test our mental boundaries, it demands that we think differently. While the graph is speculative, we need everyone to buy in. A curve revealing a future of mediocre growth is not inspiring anyone to dive in. If we want buyers to come, we must first believe in the future we are building.

Some conject that the demand does not exist. To rearticulate the problem, remember that the critical component is lowering the cost enough to broaden the market sample. Assuming we can lower prices, the market is expansive. Demand is not the problem, capacity is, especially if we can't see it coming and must improvise ad hoc. So, the problem becomes a question of whether we can handle the capacity, whether we can scale up enough. “Aurora Station is the answer to the world’s expanding demand in space travel” (Carter), says owner of Orion Span Frank Bunger. Conferences worldwide are brimming with these kinds of projects, and the ideas range from insane to obvious. These people are invested, operating under the presumption that there are plenty of customers to be found. They may be the next to bite the dust, or they may know something we don’t; they are betting big on it.

Table 1.4 2 Preferred length of Space Trip



1.5 Timing

The recent surge of investment we are witnessing in the space sector is commonly known as the New Space race. As we enter the foothills of the growth curve, unchecked growth will disrupt the future health of the entire industry, just as the quality of a city suffers when developers make the calls. If we make our next moves intelligently we can develop in a cohesive manner that uplifts all, investors,

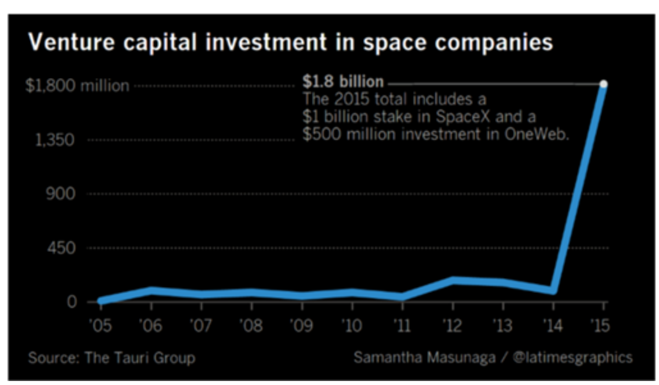


Figure1.5 1 Venture Capital Investment in Space Companies

vendors, and customers alike. The time for master planning is now. The impending 2020's will fly many companies; a concentration of force will benefit everyone. Without it, at worst the industry may never receive the kick in the pants it needs to meet its potential, and at best it will do so slowly. While accelerating the future is unnatural on its own, we're witnessing either the explosion of an industry or another thirty-year fizzle, and that is why sooner is better. For space tourism to become a reality, we must scale up. The purpose of this work is to demonstrate a strategy for accommodating the growth of the space population from tens to hundreds, shedding light on limitations that must be overcome and opportunities that can be found along the way.

Chapter 2 The solution

2.1 Shared resources

What exactly does scaling up mean, and how do we do that? As a starting point, let us examine the needs of a space tourism company. Take Bigelow for example. CEO Robert Bigelow's B330 is marketed as a fully

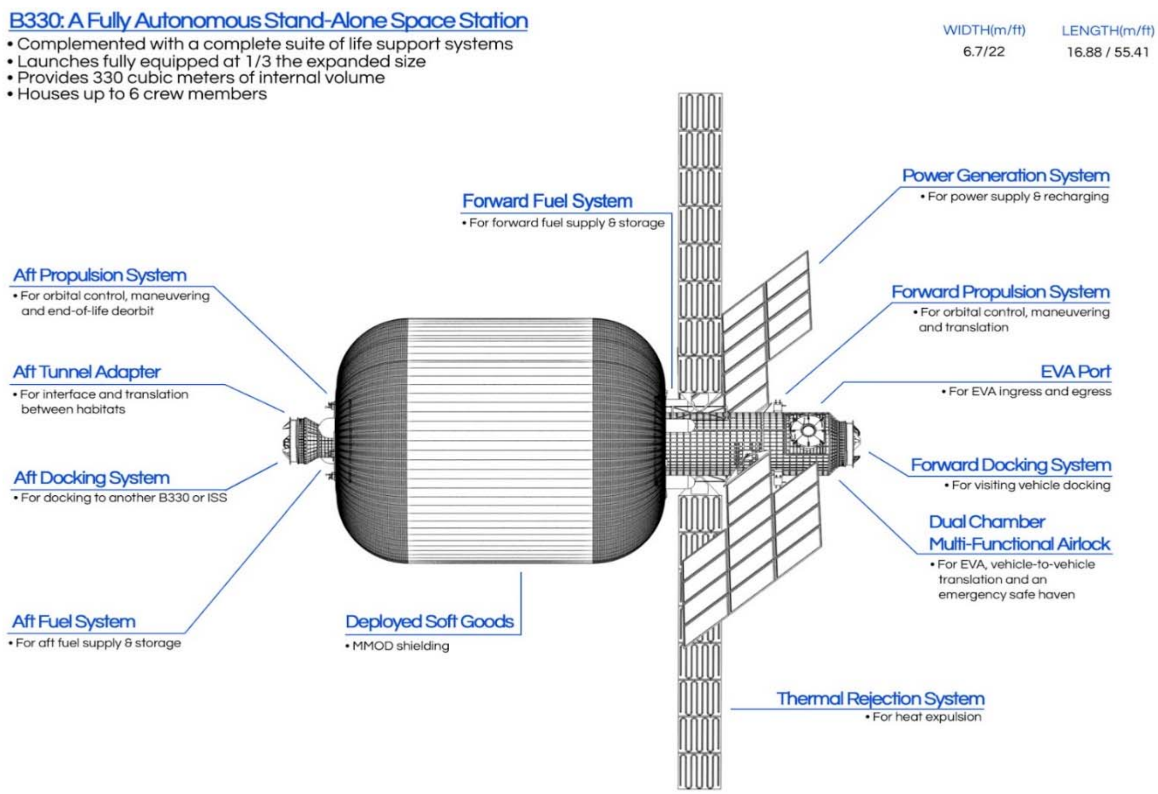


Figure 2.1 1 A Fully Autonomous Stand-Alone Space Station

autonomous space station, yet they are often depicted flying in a group. If they were self-sufficient, why would they need to aggregate? Additionally, why would we want to gather so many people on a single station? Some argue that many smaller stations represent a model for decreased risk, but if our aim is not to compartmentalize total risk in many stations but to decrease total risk, greater populations collectively can afford more redundancy.

Transportation lines, for example, are more streamlined and organized when approaching a single station as compared to many. If you study their marketing images, you see that the modules are no longer truly stand-alone, they are sharing a spare vehicle for emergencies and a logistics module providing support. The most impactful opportunity to be found is one of pooled resources. Under this assumption, the barriers to entry become much lower as specialization eases the startup cost. Perhaps this could be enough that future space tourism companies will not fail.


Figure 2.1 2 Shared Resources

Moreover, under this model companies may be able to team up to increase their amenities to attract more customers, while splitting the bill to simultaneously decrease costs. Imagine ten separate stations. At a certain point in their growth, they can each afford to purchase a luxury module. This amenity draws new passengers because it is novel. For Axiom, it is their room made of glass for a half dome view of Earth. If Mr. Bigelow decides to host a stand-inside-of-a-bubble-pit on their commercial station, how many times would you do it before you are bored to death? It may be enough to attract new guests, but it will not be soon before they schedule a return flight, as guests grew jaded to that on day four of a two week stay. If the ten separate stations were attached, however, and the amenities shared, the experience is much different. A fortnight stay is now insufficient to experience all that the super-station has to offer, and a return trip is booked on the ride home.

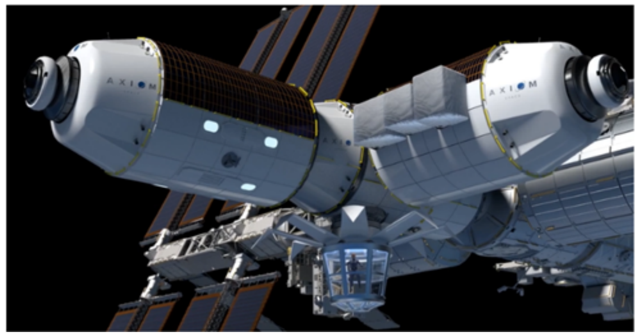


Figure 2.1 1 The View from Axiom

Furthermore, that shared amenity could be under the ownership of a business who specializes in only that, delivering potentially a more developed idea. Scott Benjamin declares that “competition will evolve based on a focus on product differentiation among these firms as opposed to the reduction of ticket prices” (Benjamin) which, as we determined, was one way to expand our customer basin. If we reframe the locus of control, our products will evolve from big glass windows to space diving, for example. This is also how a commercial station could one day afford civic scale projects. Financially, this module is funded by a separate investor, again taking the burden off the host. It could also be flown nearer to the launch of the host station to increase the station’s desirability before the station owner traditionally would have the means to afford it. While this is something that could be done in either scenario, the latter privileges the standard of collaboration and community fostered on the International Space Station, where “technology is still developing, and the relevant companies are maintaining a healthy mixture of competition and collaboration” (Heracleous).

Gallivanting with our free flying stations is like waving a victory flag after securing a few rich and reckless and proclaiming success. Ask the founder of any space tourism company to date to see that success includes a measure of longevity, and in this case, we're aiming for permanence. Many of these companies plan to build on the ISS and break away to float in the abyss. It is imperative that they stick together to capture this opportunity, but we must act now in preparation for them.

2.2 Renting Space

How do we transition from clusters of modules, owned by single entities, to massive numbers of passengers? We must first make it easier to build a station. Besides for the lack of demand, a reason why there aren't many human-rated commercial vehicles in space is the high barrier to entry into the market. Science fiction gives birth to fantastical ideas of how space could be, but of course we don't take it seriously because there is no reasonable path to fruition. The obstacles are too great, their task is too difficult, there is no precedent, NASA would never approve, but most importantly, it's cripplingly expensive.

David, the founder of Orion Span, would love to build a space hotel, but he must provide food, water, and shelter for his guests. Food is simple as it comes packaged from Earth, but waste is a burden. Water is heavy, and high paying guests will expect much more of it than trained astronauts are allowed today. A reclamation loop is complicated when diets are not well controlled, implying that a large percentage of your fresh water will come from the ground. Shelter is not simple. The air must be pumped and evenly mixed around the station as there are no natural currents; this alone is enough to take a life. It must be monitored and scrubbed for contaminants, providing the correct amounts of O_2, N_2, CO_2, and the percentage of trace contaminants must be limited to acceptable air quality standards. The temperature must be just right, which is loosely like trying to golden a marshmallow in a furnace. Humidity levels must be balanced. The proper pressure must be maintained. Power must be provided via solar panels. It must be able to fly, it must be bulletproof, and it must fit into a tiny little can. It can make no mistakes. No pressure. If we could provide these services for them, or mate them with someone who could, the result would be micro stations that pay a use fee, resembling something of a rental space. Now the dreamers may be taken seriously by investors, and the limits to their creativity are the limits to the station's success, as they are responsible for creating demand.

These systems should perform like the infrastructure of a neighborhood; the lines are laid ahead of time, and the plot is ready for a structure to be built. It is not magic, it is the same model we use on Earth. Now David can forgo the debilitating costs of designing expensive technical systems and focus on his mission. It is a much simpler financial burden to build a house if you have access to utilities on demand. The beauty of this idea is the potential to escalate incrementally with the natural growth of the market. What is needed is a strategy that escalates alongside the growth curve, implying many smaller distributed systems over larger ones spook investors. When David has room to build another module, he builds one. What is realistic is a repeatable decentralized strategy that scales with users, ready to install on short notice.

In addition, stations are much more affordably serviced if consolidated, just as urban communities are more efficient per capita than rural communities. It costs too much for the servicer to fly to each of the individual stations, but together a neighborhood can afford this. Cooperative inclusivity adds up to more participation. Factor in competition, and the companies competing for David's dollar are trying to one up each other in terms of offering, and while that may a challenge for the companies, it's what guests want, so it's what David needs too.

2.3 Economic Bootstrapping

In the standalone configuration, supplies going up must come on the same ship, as there aren't multiple ships coming to and from each day. On a massive station someone might recognize the opportunity to thrive as a specialized service provider, allowing consolidation of the supply chain. Congregation might be the only way unsubsidized businesses can survive in low Earth orbit, but as a breeding pool of ideas and opportunities, it is also a great way to support economic maturity. Just as NanoRacks found a way to fit into and profit off in space society, others will to; where the earth is fertile seeds will grow. Suddenly, a visitor notices that all the disposable twist caps on their toiletries are going to waste and could instead be collected, melted, and resold as bulk material for profit. This evolves into a privately-owned material stockpiling and recycling operation who becomes a client for returned lunar and asteroid regolith. Another found a way to transform recycled spools into plastic bags to hold used water that acts as more affordable shielding. Almost by accident what we've done is generated an intertwined economy that evolves beyond imaginable limits.

Based on a free enterprise it will grow naturally, it will evolve and adapt the quickest, it will encourage competition, and it will derive the most inventive and excellent solutions. During the ISS's formation, groups could not agree on which system to use, so while some systems were upgraded, others were no longer compatible, requiring jerry rigging and adapters. A capitalistic system offers the opportunity for a group such as Lockheed, who specializes in life support systems, to capitalize on their product, and while they too inevitably will use adapters, it is vital to their survival that they plan efficiently and limit these kinds of growing pains.

Given the opportunity for specialization, citizens will fill the gap. Could these insightful opportunities occur in the scenario where tourism starts with the free flyer? Absolutely, but it takes time and attention for these ideas to grow, so the best way to prepare the soil for their arrival is to provide access to as much light and water (people and resources) as possible. When more people engage, it fosters an individually competitive marketplace where the best products win, but where everyone is collectively invested in cooperative survival. This is the way to craft the richness of a diverse economy that will break the model of space as we know it. If we fly alone, we cannot foster the depth required to evolve the product to draw customers to decrease market risk to increase our odds of success.

2.4 Placemaking

When we think about what space visitors want to do, the answer is very clearly that they want to see. Once a city grows, however, it forms its own sights; one cannot visit Los Angeles without experiencing Hollywood Boulevard, but the first visitors came to see the ocean. Viewing will always be a part of it but limiting our future to only that is naïve. This station, which began as an exercise in Earth viewing (or even a display of status), becomes a cultural phenomenon.

Placemaking is an important part of designing the built environment. Those who have lived in city without a downtown know that a city without a heart is a city without a pulse. The International Space Station, the Moon, and Mars serve as destinations beyond Earth, but without them it takes much more imagination to answer the question of where we will go. Creating a place to go to in an ocean of nothing is a strong reason to aggregate. We have the supply and the capability, I'm proposing we can create demand.

Once there is a clear destination, there is a snowball effect, and suddenly everyone wants to be where it's all happening.

2.5 Uplifting an Industry

Holistically thinking, the space tourism industry, more broadly the entire space industry could use a stimulus. We have decades worth of expertise laying around, yet there is little demand for it. This could be that possibility.

There are many benefactors of this newly formed industry. If the biggest hurdle is flight cost, for example, the best thing we can do for launch providers is to create demand for their product to assist maturation. The supply chain that would be necessary to support many guests would be expansive; more launches means more affordable launches. Once you have customers, many will step forward with a plate to get a piece of the pie. It means more business for every industry affiliated with spaceflight.

Space companies such as NanoRacks have reinvested their profit into growing their business and the industry has felt that reinvestment. Their success has birthed imitators, but they welcome the competition and in fact see it as a success, as their goal was always to foster the market. By remaining in free flyer configurations, we're missing out on market breadth.

2.6 Conclusion

The growth ripples beyond cislunar space. The companies established in low Earth orbit become a customer for ULA, ACES program, for instance, who want to prospect for lunar materials, an important checkpoint and an ability that is helpful to go further out in the solar system. Cislunar space is vital as a checkpoint to accessing deep space. Once established here, it is a physical foundation, and a financial proving ground. The knowledge gained in pursuit of this feat will pull from the woodwork many potential stakeholders for this type of work. Inspiring participation means a quicker economic acceleration, and accessing the moon, asteroids, mars, and alpha centauri sooner. If space tourism is successful, the space industry will be.

Chapter 3 Description of the Design

3.1 Elusive Future

Now that we have established why we must pursue this idea, we must entertain how it could be done. There are substantial challenges ahead, and while we have some idea of the work cut out for us based on what has been learned, the scale of our endeavor is unprecedented, and to declare an answer for unknown challenges is naïve and premature. It is difficult to speak about a station as a finished element because it is always evolving and in doing so gains unpredictable capabilities and characteristics. It is speculative, and as the past reminds us, a single invention can reroute any likely future. The economic forces of the next decade off Earth will define the stakeholders, and the nature of these relationships will determine what shapes the station. In a capitalistic system a flexible and evolving campaign is superior. As such, any concrete plans will blindfold us to the possibilities of progress towards this future that we cannot imagine.

What is demanded is not a polished and complete design, but a minimal supporting infrastructure. This evolution can be generalized into growth strategies and checkpoints, always with a nod to adaptation. The best cities have grown naturally, and with awareness can be healed posthumously. Intervention, rather than perfect planning, is key, because the important thing is that we get started.

3.2 Determination of Orbit

The massing of the station is heavily influenced by its environment, so it is important to start by establishing the orbit of the station logically. The sun-synchronous orbit, accessible globally at dusk and dawn, is advantageous in that it provides power all the time, a necessity for a station with unknown power requirements. It is a stable, yet intense, thermal environment. The radiation levels are still somewhat tempered by Earth's atmosphere and the atomic oxygen levels are less than at lower orbits. The lowest altitude at which this orbit can be performed is 600km, and while that is farther away than the ISS, it is safer in that it is less littered with debris. At a velocity of 7.55 km/sec, and an inclination of 96-98 degrees, the equator is passed 30 times a day, 830 miles west of its previous mark, once every 96 minutes. It is accessible twice a day globally, at the beginning and end of each day. The

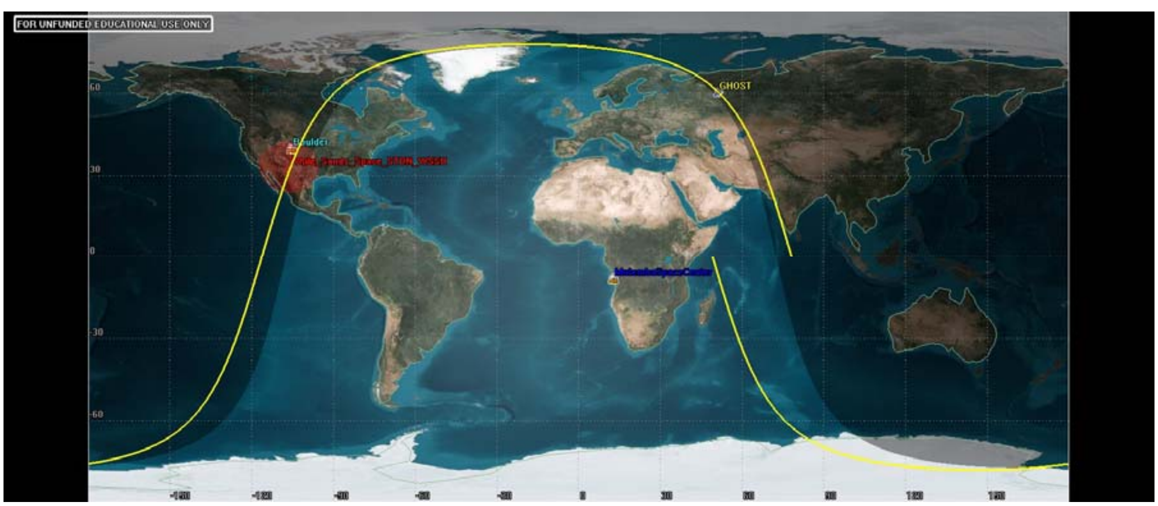


Figure 3.2 1 Sun Synchronous Orbit

polar orbit requires about 30% more energy to enter than a due East equatorial orbit, but this is the trade off to capture the other advantages.

Looking down from this trajectory, one will always see a sunset or sunrise, as the station's ground path is on the dusk/dawn line.

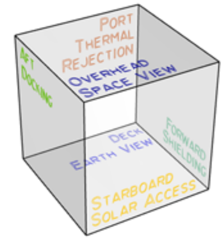


Figure 3.3 1 Simplified Cube

3.3 Environmental Growth Factors

The station is always perpendicular to both Earth (Earth is always down) and the sun. Figure 3.3 1 shows that solar arrays will be located on the starboard side of the simplified programmatic cube in our orbit. The forward direction of the craft is more susceptible to damage, so that side of the cube should be reinforced with whipple shielding from debris. A large profile also creates undesirable drag. Docking can theoretically happen anywhere, but analysis of flight corridors and preventing overlap of the cube's other needs locates it behind the station, or aft. Heat must be rejected, which must be done away from the sun. Some constraints are more flexible, such as windows, and project their limitations onto the configuration less than others, such as the docking ports, which can certainly create a poor configuration. Anticipating the subtle

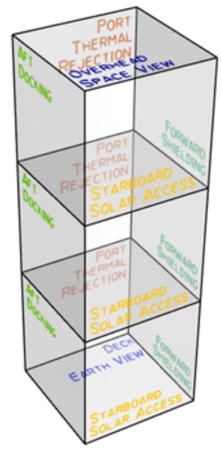


Figure 3.3 2 Vertical Growth

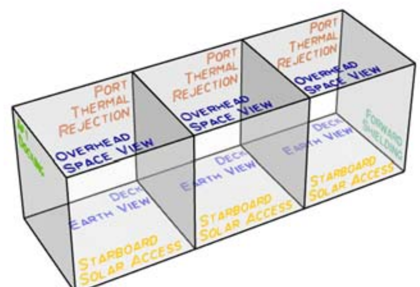


Figure 3.3 3 Linear Growth

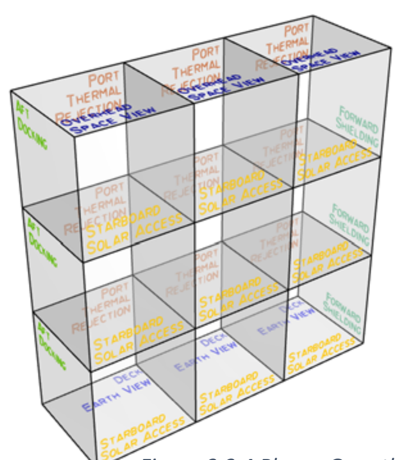


Figure 3.3 4 Planar Growth

ways that these foundational decisions affect a station is difficult. For example, a participating tenant may decide that the most important factor to design by is maintaining the visitor's circadian rhythm, insinuating an arrangement of the station that was never previously imagined. Depending on the growth scheme chosen, the layout of station elements vary. To better understand multiplication of the blocks, we look closer to the functions.

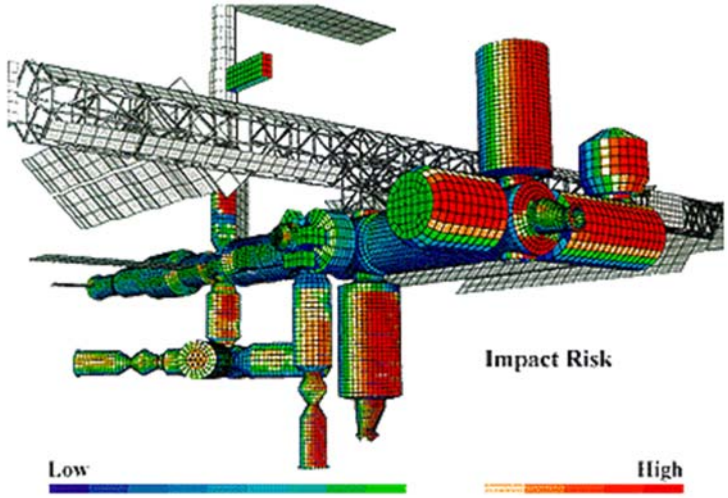


Figure 3.3 5 Impact Probability on the ISS

3.4 Earth Viewing

The best situation for viewing would be a dome facing the Earth, like Axiom's cupola. But if you put many people in this dome (or any concentrated place on a station), the nearby escape vehicles will not have enough room to park. And if you multiply a smaller dome into many arranged in a plane facing Earth, they block each other's view. Attempting to let this be the most rigorous constraint is a slippery strategy. While floating above the entirety of the Earth may seem idyllic, the eyes cannot see the entire Earth in one perspective anyway, as our field of focus is narrow. On an airplane our attention drifts toward the spectacular view beyond the windows, even when we are sitting in the middle of the aircraft. A few degrees is all that is necessary, and this can be accomplished nearly anywhere on the station, as Earth's horizon lies at 24 degrees below horizontal.

3.5 Solar Collection & Thermal Rejection

Solar collection is perhaps the most stringent requirement, as we must have power, but we don't know exactly how much. We should therefore hypothesize a scalable growth strategy. A collective system proves ineffective after some analysis. If the solar panels are arranged in a wing like position they are sure to block the view. They also complicate the traffic pattern, requiring an additional forward approach path. Another downfall of the wing configuration is in long term growth; they don't have enough room to grow before invading on nearby flight corridors and extending the panels away

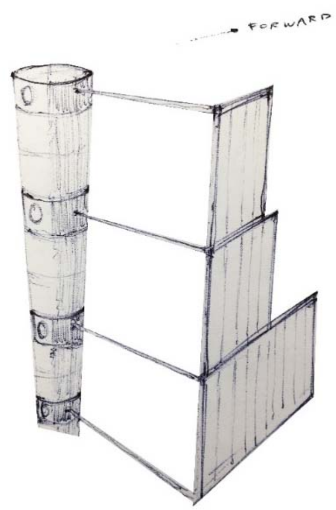


Figure 3.5 1 Centralized Power Collection

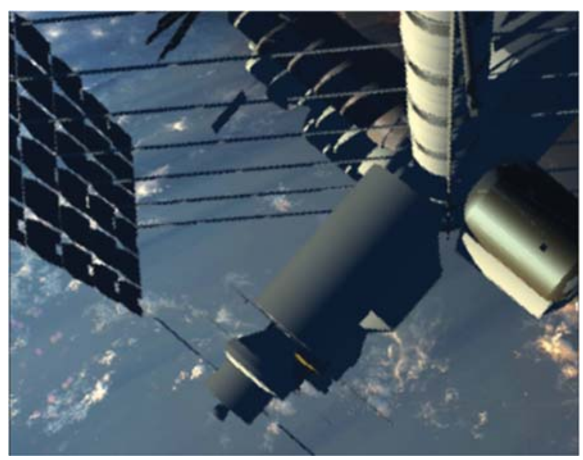


Figure 3.5 2 Shadow of Inequality

from the tunnel to create more area seems like a poor idea due to structural loading and access for repairs. Lastly, a collective system goes against our capitalistic growth strategy.

Therefore, it is simplest to require that anyone who participates must provide their own power. The challenge occurs, in that all four quadrants cannot gather power equally, calling for a rotisserie strategy, where, as the name suggests, all have a quarter share of a rotation in the sunlight, and must use batteries to make it through their 20-minute dark cycle. Body mounted panels on the tunnel are not a viable option since nearly all the surface area is obstructed by the parking spaces.

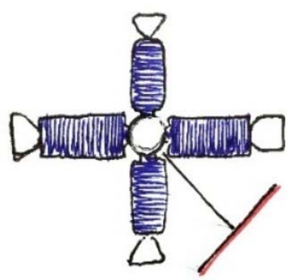


Figure 3.5 3 Stationary Centralized

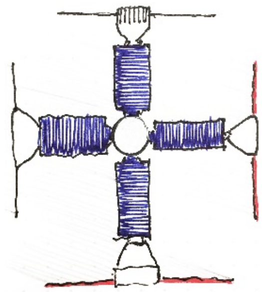


Figure 3.5 4 Rotating Distributed

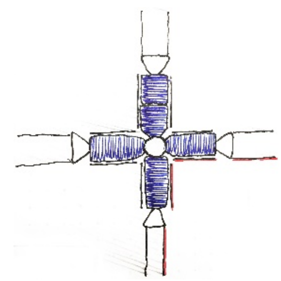


Figure 3.5 5 Rotating Body Mounted

While deployed panels offer the best surface area for capture, body mounted panels take the demand off the batteries, as panels can be mounted to both sides of the vehicle and power can be collected twice as often. Just as in traditional architecture, our windows are at odds with our control of the sun's rays. In this case we want to capture them, but usually we are trying to block them. Generative and parametric modeling tools may shed light on a solution, incorporating a louvre like design that allows sightline geometries and also captures ray. Or perhaps technology will catch up, and our windows and solar collection will become one. Until then, body mounted units provide a superior experience for one reason; imagine gazing out of the window to see the view, but instead, you see only a metallic frame.

3.6 Docking

We also must locate docking where the people are, so that in the event of a catastrophe everyone is located near their ship. Docking in a single place would create a traffic hotspot and an event could cut off access.

There exists a theory that recognizes that the amount of energy imparted onto the station by docking vehicles is significant enough that if vehicles docked frequently, the orbital decay due to drag could be eliminated. This would require that the docking is always done from the deck or aft side to benefit from this action. The same concept could be entertained for orbital control. Fundamentally, the station contains many reaction control systems, located on each of the visiting vehicles. While it is unproven, this is an important idea to consider because it could mean that the infrastructure required to maintain the orbit is far less extensive. Of course, if you did not want to rely on visiting vehicles for reboost and maneuvering, you could house those systems onboard, or the cost to hire those services could be shared, too.

Before the traffic to and from the station becomes overwhelming, it will be important to define best practices for approach corridors and proximity operations. For starters, all vehicles will approach and push-off ascending aft of the station. Vehicles approach from behind so that they don't cast a shadow on the solar arrays. They approach ascending because to do so they must accelerate to match the velocity of the station. If they were to approach descending, or approach the front of the station, there is the possibility that in decelerating the reaction control systems will plume the station. Instead, the approaching ships will match speed, and final approach will be done with airjet systems. Likewise, when undocking, mechanical actuators will push off, and airjet systems will be used until the craft is out range and ready to translate away from the station by boosting away from Earth. The ships approaching and withdrawing are organized by the secondary rule to pass on the left, preventing overlap of corridors.

With a large population, it will become necessary to enable frequent resupply, so cargo bay locations will be distributed to prevent traffic hotspots and single points of failure. It is likely that not every module will use their port location, and it could instead itself be hired out for these purposes. This exercise results in dramatically different station layouts than what we have seen, as the constraints are unique. What began as a way to encourage early growth will become complicated quickly. In the event that a unit buildout becomes elaborate, then it could make sense to switch to a new strategy.

3.7 The Node

If we look again at Bigelow's cluster of modules, they are joined by a central node. The node's primary use is for circulation, so it is expensive but necessary volume. In theory, the node is comprised of a ring of berthing mechanisms. If you want to build up these rings you must provide a separation distance for the modules parked to them, requiring a spacer. This spacer should be as lightweight and compact as possible, insinuating not a rigidized shell but an inflatable structure, which could serve the bonus function of dampening vibration and noise across the system. The best thing it can do consequently is to perform its connecting function as efficiently as possible and seek out opportunities to be of value so that it is not thought of as wasted space. What if the node could contain value adding functions such as life support backup systems, distribution of fluids, air, and electricity?

The environment of the nodes must be tempered, and we look to the tenants to pay for that service. A utility chase, something like a power line, and air duct has plugs every 10 meters for vehicles to tap into. While it makes sense for all to pay for this space collectively, it also makes sense to have a single specialized system do the work since the scope is clear, as opposed to asking parked vehicles to condition space beyond their hatch. If a collective system were utilized for every utility, it would need to be designed for the max scenario. Due to the prohibitive cost of the unpredictable nature of tenant requirements, this is unfeasible. Waste and water will be located only in tenant ports, as that system will not soon be centralized, but an external backup tap would be invaluable.

The node lets the modules act as safe havens for each other. Systematically, this looks like multiple redundant systems; even though they should be self-supported, the corridor acts as a life rope. Divide this cost ten ways and stretch it over a decade and this safety may be worth its weight. It is imperative that the infrastructure is minimal, loose-fit, and evolvable, so that it cannot become a burden to those who rely on it.

As a connector, the node must support loads of the crafts (table 3.7 1) across the entire structure, whether it be via an internal or external skeleton. This truss will contain attachment points to support the tanks necessary for the tenant's environmental control and life support systems. Along these rail-like structures located opposite each other, an arm will glide, with close access to the berthing mechanisms. Having two arms decreases the likelihood that an extra-vehicular activity will be necessary, and as more crafts aggregate both may be necessary for assembly. If the arms cannot keep pace, more than one could be placed on a rail, or two more rails could be installed.

Table 3.7 1 Mass of Outfitted B330

Item	Mass [kg]
Inflatable Shell Assembly, including Liner, Bladder, and Restraint	1,265
Multi-Layer Insulation	235
Micrometeoroid and Orbital Debris Protection	3,208
Other (Windows, Deployment and Attachment Systems)	204
Central Core Structure, including End Cones	1,405
Water Containment [31] (Enclosing 18.8 m^3 and covering 40.1 m^2)	142
Radiation Protection Media (A 0.0574 m thick water shield; areal density 5.7 g/cm^2)	2,304
Initial Inflation System	502
Avionics and Power Management and Distribution	1,398
Total Mass	10,663

For the sake of versatility and to follow historical precedent, four parking spaces are arranged per layer. Other methods may be more compact or more efficient in certain situations, but simplicity is the winner here as the usage of these spaces is unscripted. The height of the space is nine meters (followed by a meter of keep out space) and the width of this space is also set to nine meters. This number is determined by the capability of launch vehicles fairings and could grow in time. Extra space should be allotted for external racks, body mounted solar panels, and radiators. Between each of the quadrants is a meter of keep out space for the external trusses and robotic rail. The house shaped is derived from consideration for the viewing rights of the layers above.

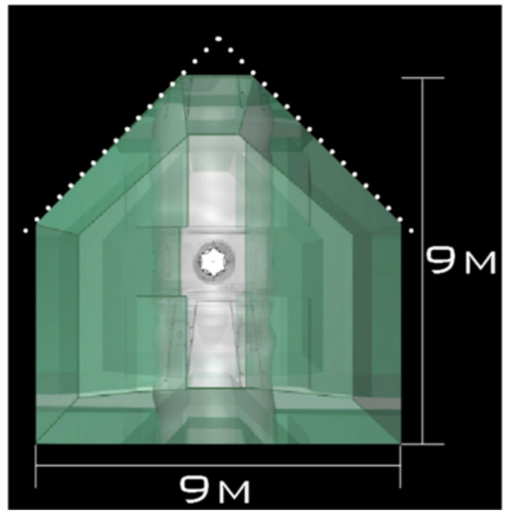


Figure 3.7 1 Parking Space Limits

It is premature to decide what launch vehicle this will mount, as our vehicles are currently evolving rapidly. Ideally, our expandable node can launch on something like the extended dragon truck concept, where the crew vehicle could still perform its mission of delivering people and supplies, the launch would not be solely for the node's delivery, and the dragon could subsequently serve as an emergency vehicle.

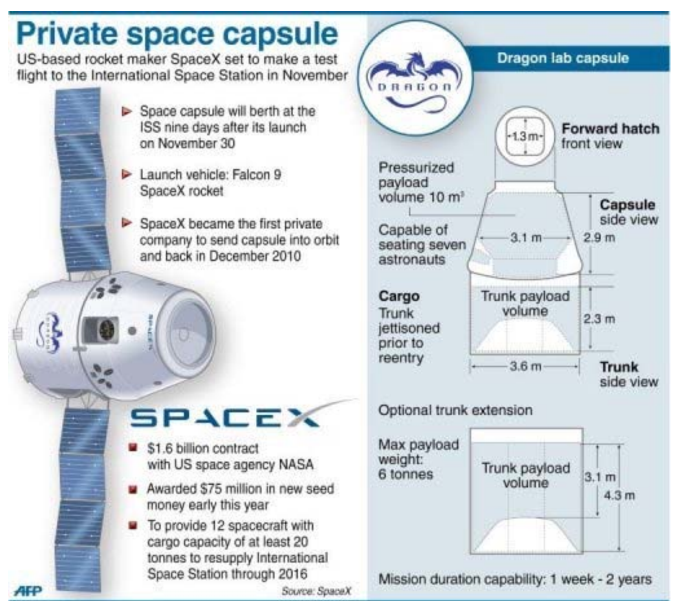


Figure 3.7 2 SpaceX's Extended Dragon

3.8 Limits to Growth

As the station grows, launch vehicle capabilities will too. As a result, new tenants will be larger, and heavier. This is a problem if weight in a layer is not balanced in the x and y axis, so they should be paired with other modules of a similar mass. If an occupant would like to add additional modules to their port, the others in their node shall also, to build in a stable manner.

Figure 3.8 1 X & Y Growth

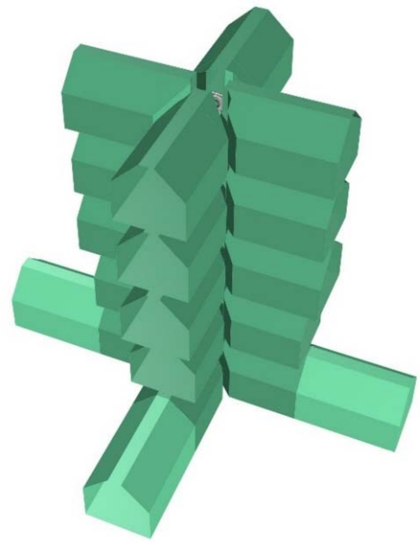


Figure 3.8 2 Vertical Growth

Our solar strategy breaks once the number of passengers hosted by a single module exceeds the capabilities of the vehicle attached. When more than one docking port becomes necessary, it must occur on a tenant's side port, resulting in a wider profile and casting a shadow on the neighbor, reducing their solar area. To overcome this growing pain, we embrace the wider profile, expanding the number of modules parked side-by-side from a single module to three, as seen in figure 3.83. If tenants desire a layout beyond

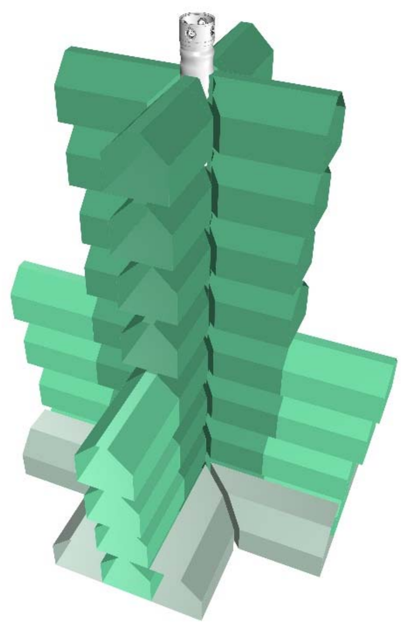


Figure 3.8 3 Concentric Growth

the linear growth configuration, they must adopt two ports to the tunnel, but can then configure an entire layer. If they desire even more space, they can rent ports on the node above. At this point, their station has the qualities of a fully formed three dimensional free-flyer but maintains its lifeline to the other stations.

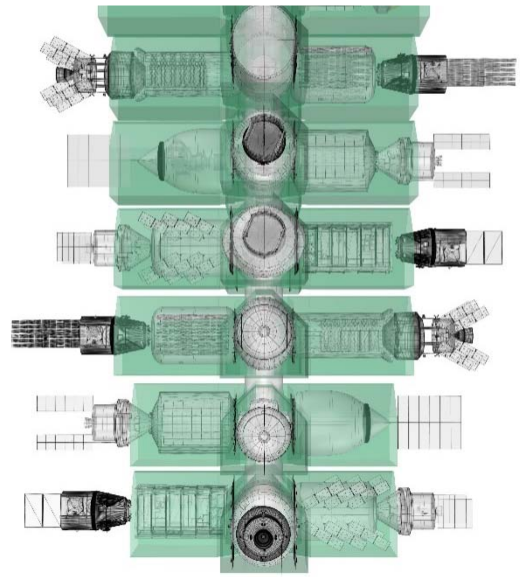


Figure 3.8 4 Expansion Xxample

There are human limits to this growth. In urban design there is a concept of the five-minute walk, defining the maximum walkable distance before the scale of the city overwhelms its user. As this is based on speed, we must first know how fast we will move in space. Floating on the station is similar to swimming, but without the drag. It is based on how much force we can exert through our arms and legs and also on a comfort level of collisions and the ability to decelerate. On Earth, we walk about 80 meters per minute and we swim about 54 meters per minute. But float speed is probably even slower; I don't imagine anyone on vacation in a space station will be in a hurry. One meter per second is as fast as I can tolerate talking into a wall, so for a safety factor of two let's assume half a meter per second as an average speed. This allows us to cover thirty meters in a minute, 150 in five minutes, and 300 in ten minutes. Before we go any further, we should also consider the emergency life support systems that each person will carry. If personal life support systems can only handle a ten minute evacuation, it would be unwise to build a tunnel that takes 15 minutes to navigate end-to-end. While there will be life support systems in the node in the event of vehicle failure, this is a good starting point for determining the max length of the station.

The limits are not the focus of this work; the key is the simple growth strategy that allows the first few layers to be built very quickly, allowing growth to meet the demand that we are creating.

3.9 Pipe Building

As we extrude, our passenger count grows, as does our overall volume of the nodes. If we were to build this traditionally, berthing one module to the next, we will run into a bottleneck at each berthing mechanism. "You don't go to space to sit in a bag," says Larry Bell, and right now each of the nodes is just about the same as any other inflatable. Here is an opportunity to develop a construction method that allows us to build continuous pipes, a place to find relief from the module, a place to stretch your legs,

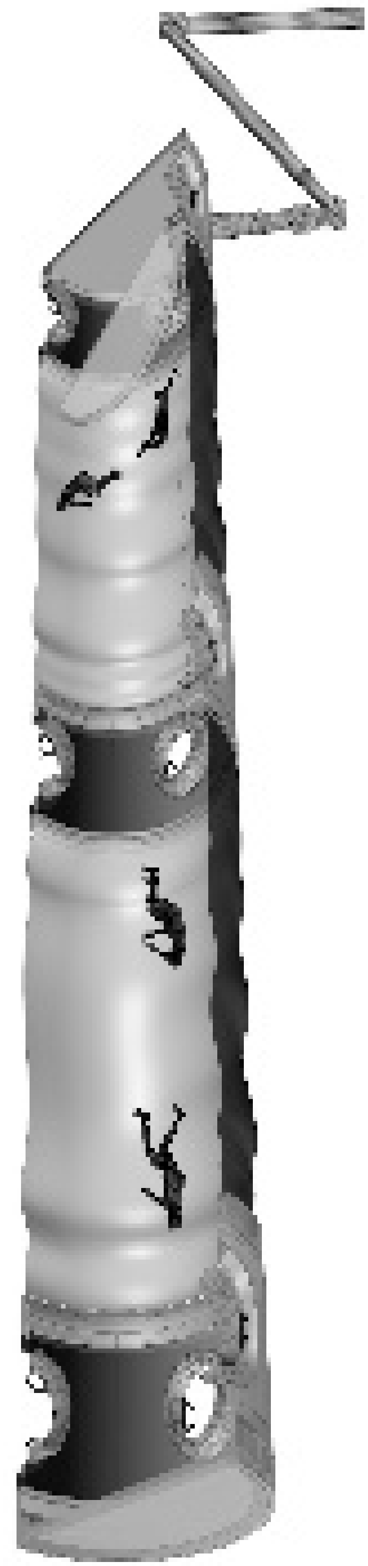


Figure 3.9 1 Internal Dividers

with long sightlines to give your eyes a break, instead of disjointed spaces. The challenge this creates is that to remove the end caps you must berth a non-pressurized section to the pressurized core, and this is tricky. It would require a double walled system comprised of an external wall that could be manipulated externally by robotic arms, allowing the unpressurized section to be connected and then pressurized, and an internal partition that could then be removed.

Figure 3.9 2 Robotic Installation

In the event that there was a leak in the core, the partitions could isolate the sections. Personal life support systems would engage, activated remotely, and passengers would need enough time to get to their desired side of the divider. These personal life support systems are compact, so they have a limited capability, which informs the design of these emergency systems. Our systems however, should be continuous, having the ability to pass through the section while it is repaired from the inside or out.

3.10 Public Space

What we have now is a tunnel, and a new set of problems. It should be thought primarily as a thoroughfare, as there will be many passengers passing through at any given time, and so we must designate a space for moving. Thinking about gliding, we want a firm object you can push off and catch with your hands and feet, something like a rubber without sharp edges or traps that you might bash into or snag on. We cannot expect things to move themselves, so a zipline will complement the paths. The mechanical runs, a set of power lines and air ducts, have been placed behind the elevator rail, strategically distributing and collecting air. The light source is hidden and provides an ambient glow. As we know the ISS was a noisy environment, but the soft inflatables dampen the noise.

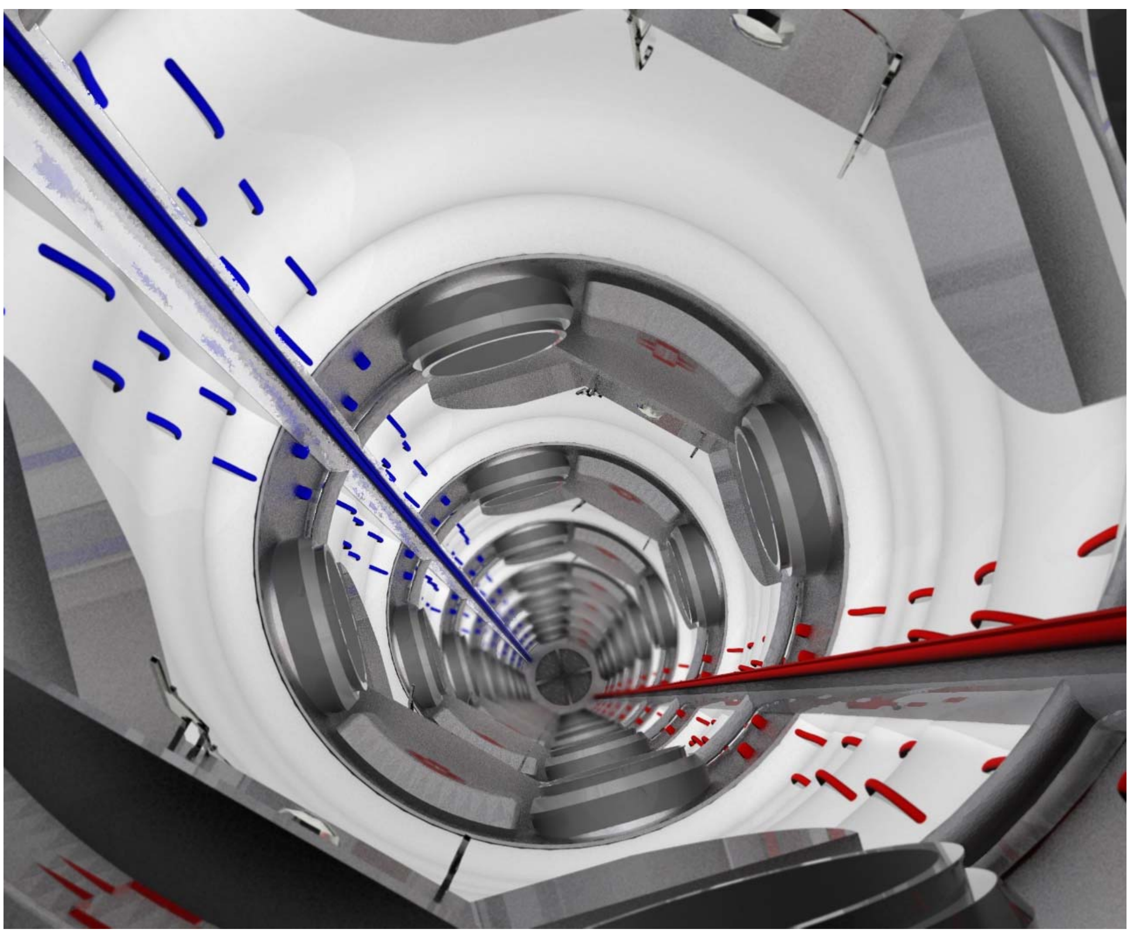


Figure 3.10 1 A Public Space

As navigating the world of x, y, and z will be new to most, it would be beneficial to consider electronic assistance, something like a heads-up display to point the way. Such a system could assist in safety procedures, such as recognizing density laws to limit the number of passengers in a specific area based on the capacity of the emergency systems and intelligently sorting guests to identify the nearest safe haven. Tenants would be allowed to use the space near their closeable port to attract guests, in the same way businesses put out sidewalk signs. A digital infrastructure (Figure 3.10 2) could perform the same function, without the mass and space penalties.

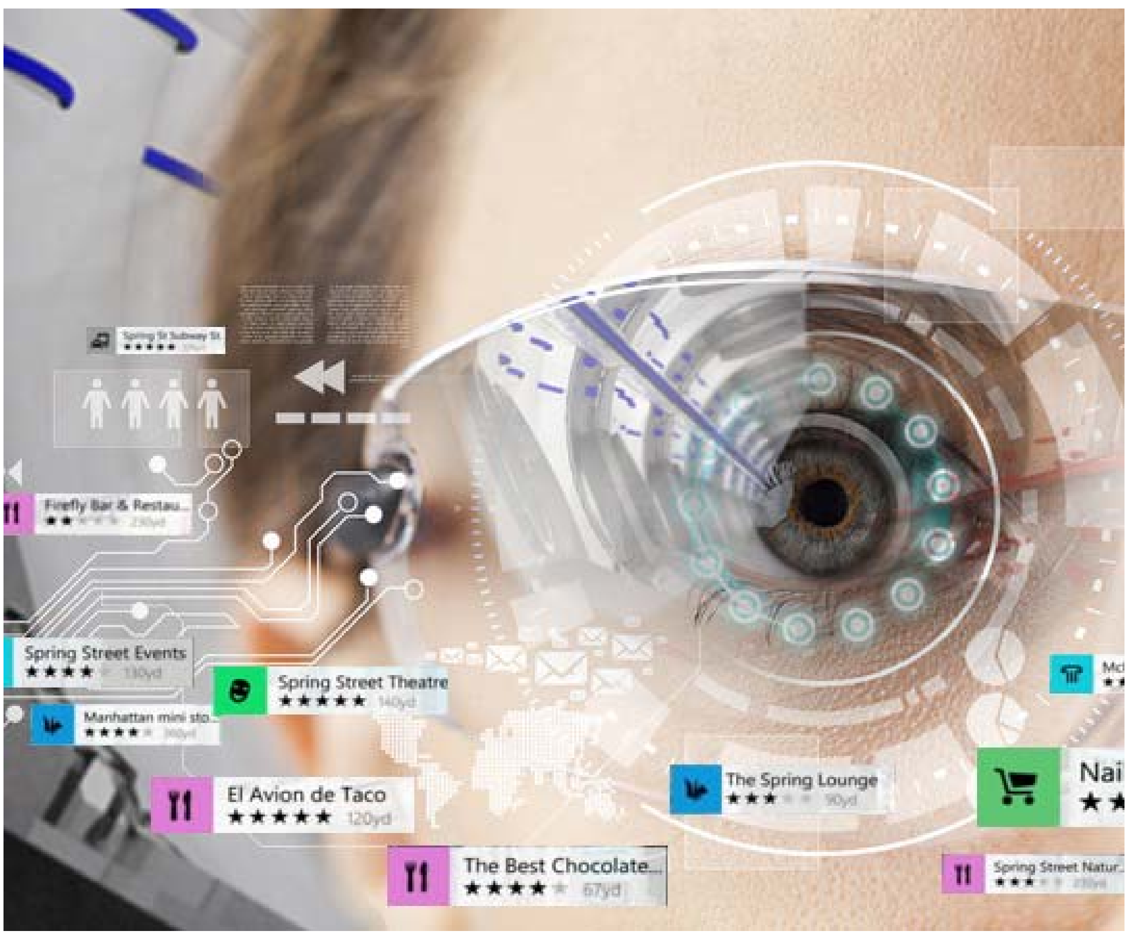


Figure 3.10 2 Heads Up Culture

Density is unavoidable and even desirable. Consider a dining table, for example, where your personal volume is something akin to the space you have on a sidewalk (2m3/person), yet we don't think of this as a crowded situation. It's also inconsistent; you can imagine floating leisurely by a group of people huddled closely mingling. If the tunnel were 15 layers (150 meters), it would be roughly the length and volume of two 747's. There would be far fewer people (350 if 5 were assumed per port), but still there would not be room for everyone at once. Assuming even distribution, this would be 5.5m3/person, something like standing in a 5' x 5' x 8' box, which is claustrophobic before long. Drawing customers from every time zone reveals the advantage of offsetting peak loads. Perhaps if the traffic could be coordinated and guests spent 25% of their time (six hours a day) exploring the tunnel we could reach a more reasonable personal volume of 22m3/person or 10' x 10' x 8'. Tunnels inherently have a mesmerizing sense of spaciousness about them, and while this scaffolding public space may not feel like a concert hall, sidewalks are successful community spaces, too.

What began as a shared responsibility now becomes a redefined purpose. If a function of the tunnel, which from henceforth shall be coined as Portal, is to be a passageway from one programmatic element to another, and the visitors here are from the world over, this is not just a hallway, but a runway of cultural intermingling, an accidental social scene, where guests interface with a diverse gathering of users. Our node is no longer dead weight but adds priceless value as the first social realm in space; just like a popular pedestrian street, we've fabricated a desirable destination, which is especially important when space is infinite.

At this point, the concept has been declared, the design challenges have been identified, and the work has been divided and sorted for the specialists. The interiors can be handed to the interior designer and the engineers can address their respective hurdles. This presentation can be made to the owner of a potential free flying station, and perhaps they will expand their horizons. Potential service providers can look at this and ask if there is room for them, and most importantly, common folk who have never considered space a place for them can look on and say "wow, when can I go?"

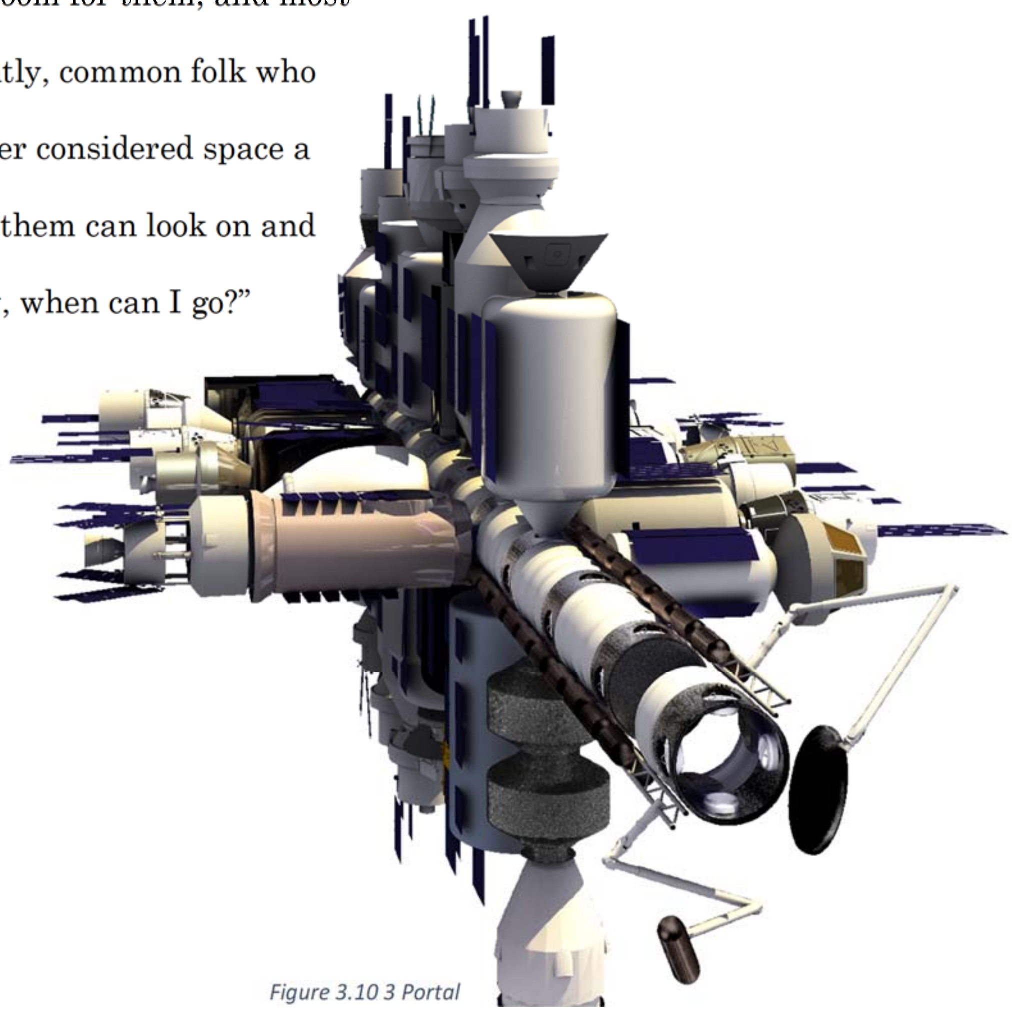


Figure 3.10 3 Portal

Appendix

Vision

To place the pale blue dot in the eyes of humanity,

because the overview effect has become necessary.

Mission

Hypothesize the infrastructure that would be necessary to host a thousand minimally trained astronauts, under the presumption that it will require this kind of magnitude for space tourism to be successful.

Risks

- People are fragile.
- Return on investment is not guaranteed.
- Technological development is expensive and time consuming.

Assumptions

- The idea of space travel will become commonplace.
- The costs of space travel will fall over time.
- The demand for tourism will grow faster than the ability to meet that demand.
- Tourism will be a commercial endeavor, so risk adverse legislation will not be an obstacle. Public funding will not be available.
- Launch costs will fall to the point that the supply chain necessary to support a population in cislunar space will be justifiable.

- Medicine will fill the need in assisting the adaption of untrained astronauts to space travel.
- Debris will be removed as more people inhabit LEO.
- Robotics will evolve to enable in-space assembly, and eventually in-space construction, of components.
- The first multiport (Portal) will be delivered to the International Space Station, or an equivalent platform.
- Tenants will provide all resources required to care for their guests, including food, water, electricity, temperature, humidity, pressure, atmospheric content, and a ride home.
- Third party providers will appear to assist tenants in providing the necessary resources for their guests.
- All guests will wear at least a minimal personal life support system.
- All tenants will plug into a collective backup system.
- Systems will be fail-safe, shall not be susceptible to single point failures.
- Modules will act as a safe zone to harbor passengers in an emergency.
- Systems will be decentralized to grow in proportion to the need.
- Docking vehicles will translate energy frequently enough to avoid the need for dedicated orbital reboost, and these energy transfers will always act on the station from the aft direction.
- The center of mass of the station will constantly shift. A gravity gradient stabilized orbit will be pursued, but the systems on the reaction control

systems on visiting vehicles will be used to reorient the station when necessary.

- Technological breakthroughs will advance the industry in such a way as to make any prediction past a few decades irrelevant.
- The overview effect will save the Earth.

Lessons Learned

People have relatively little energy to devote to imagining what you are seeing. If you want someone to get an idea, you need to do the imagining for them.

In one project I've proposed a hybrid capitalistic and socialist strategy. Wrestling with the boundaries of contradiction, compromise is an art found not in theory but in the nuts and bolts.

Human factors apply to presentations. While we care that a project is qualified by all the metrics of charts, nobody has the attention span to comprehend the intersection at every column and row. Even if we did, that information becomes anecdotal, and is best told as a story. Don't drown the audience, even if the graphs qualify you.

There is little room for the luxury of architecture in space; the constraints are many, the costs are too great. Yet social engineering, also known as architecture, which is as scientific as engineering and as neglected by engineers as human factors, has not yet been necessary in space. Here it is. May we find room in the fairing for artistry and imagination.

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